Ontological Knowledge Representation for Avionics Decision-Making Support

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***Abstract*—Air Traffic Management (ATM) incorporates demanding decision-making processes that combine information of diverse characteristics. ATM challenges aviators and airspace controllers with unprecedented workloads to maintain safety and cross-checking of multi-source information, including data from Unmanned Aerial Vehicles (UAVs). The challenge for future ATM Decision-Support Systems (DSS) is not only autonomous and reliable complex decision-making with minimal human intervention but also dealing with UAV ATM (UTM). This paper proposes the implementation of Ontologies for NextGen Avionics Systems (ONAS) for UTM. ONAS presents an operation framework and an ontology-based tool to support decision making in advanced ATM/UTM systems. The proposed ONAS approach includes a cognitive ATM/UTM architecture for avionics analytics. An ontological database captures information related to weather, flights, and airspace. Inference over the ontology is provided by a reasoner. The decision-making process is underpinned by the concept of Situation AWareness (SAW) as well as Situation Assessment (SA). The SAW approach proposed is intended to be initially used in civil aviation. A case study is presented based on different scenarios for an ATM/UTM system. The scenarios represent flight situations where the decisions made are supported by the proposed ONAS approach.**

Keywords—knowledge representation; ontology; avionics analytics; decision-making support

I. INTRODUCTION

Aerospace avionics systems are getting increasingly sophisticated with such improvements in command, control, communication, computers and intelligence (C4I). In particular, avionics systems such as the Air Traffic Management (ATM) are reaching a degree of complexity where decision-making processes are required to combine information of a diverse nature (e.g., weather forecasts, flight profiles, airports, Unmanned Aerial Vehicles (UAVs), etc.).

The Air Traffic Management (ATM) information complexity demands a huge workload on aircraft pilots and air traffic controllers who have to prioritize flight trajectories, safety, and messaging while cross-checking information coming from the different sources from a Unmanned Aerial System (UAS). The UAS coordination with ATM or Unmanned Aerial System Traffic Management (UTM) will further challenge aerospace information management systems.

A key avionics design challenge for future ATM Decision-Support Systems (DSS) is autonomous, agile, and reliable complex decision-making with minimal human intervention [1]. For example, automation is required to combine dynamic multiple data inputs within an Integrated Modular Avionics (IMA) [2]. Agility requires the ability to adapt to change. Autonomy is also afforded from machine analysis of route changes, airspace de-confliction, and performance based navigation (PBN) [3], and power assessment [4]. Hence the Federal Aviation Association Next Generation (NextGen) [5] and Single European Sky ATM Research (SESAR) [6] ATM systems require a certain degree of autonomy as well as a man-machine collaborative operation mode in order to minimize the need for aviator's and controller's intervention.

This paper proposes the implementation of Ontologies for NextGen Avionics Systems (ONAS). It presents an operation framework and an ontology-based process to support decision making in advanced ATM/UTM systems. The proposed ONAS approach includes a cognitive ATM/UTM architecture for avionics analytics and situation awareness (SAW).

The SAW approach proposed is intended to be used in civil aviation. However, it could potentially have a future use (on-board) in autonomous UAVs (to increase autonomy) and even be considered in ATM operations [7].

The case study is based on different scenarios for an ATM/UTM system which considers semantics from updates of weather maps, airport maps, and route maps. The scenarios represent flight situations where the decisions made are supported by the proposed ONAS approach. This paper presents results from representative Dynamic Data Driven Application Systems (DDDAS) [8] examples.

The rest of the paper is organized as follows. Section II reviews existing technologies. Section III introduces foundations and backgrounds for ontological decision-making support in avionics. Section IV discusses the ontological support as well as introduces the background for the case studies. Section V shows application examples for the ontological approach proposed, and discusses considerations to be taken into account when applying it to avionics analytics. The last Section presents the conclusions and future research steps.

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II. EXISINTG TECHNOLOGIES

Key developments for Single European Sky ATM Research (SESAR) and the Federal Aviation Administration (FAA) Next Generation Air Transportation System (NextGen) include the potential for ontological capabilities.

A. *NextGen*

Rainer Koelle and Walter Strijland [9] outlined progress in 2013 for semantic assurance for systems engineering in SESAR/NextGen which provides ATM security. A key example for NextGen system includes developments in the weather ontology, implemented in three operational capability phases [10]:

- Initial (2013): Significantly enhanced weather infrastructure providing modestly improved meteorological data to all users of the Nation's Air Transportation System
- Midterm (2016): NextGen begins to implement automated decision assistance tools and algorithms for managing the air space, requiring high resolution weather forecasts and observations with a greater degree of accuracy and precision
- Farterm (2022): NextGen weather must meet all meteorological and engineering performance requirements to support the NextGen traffic management systems.

B. *SESAR*

One example is the European *ATM Reference Model* (AIRM). Specifically, they looked at Notices to Airman (NOTAM). NOTAMs provide weather and emergency updates to aviators in the form of text messages. Using OWL, the system seeks a semantic-based Aeronautical Information Management system. With semantic reasoning and digital NOTAMS, efforts were underway to bring structure to the knowledge gained from text-based information

III. SITUATION AWARENESS AND ASSESSMENT

This section introduces foundations and backgrounds for ontological decision-making support in avionics.

A. *Knowledge Representation*

The cognitive approach proposed in this paper aims to provide intelligence assistance for avionics decision-making support. It relies on data, information, and knowledge. However, they are not definitely the same but related. Data are usually raw or pre-processed. Information is data with meaning. Information becomes knowledge when there is a purpose and a potential to generate action. Knowledge is the intellectual machinery which makes possible to achieve goals (by carrying out actions), and create new information [11].

Knowledge can formally be represented by means of *Description Logic* (DL). The DL architecture has two main components; TBox and ABox [12]. TBox entails inclusion assertions about properties from concepts and roles. Abox entails instance assertions such as those for individual objects [13]. The method includes:

- **TBox** component is a *terminological* formalism (terminology; system description in terms of controlled vocabularies); whereas
- **ABox** component is an *assertional* formalism (assertions about individuals).

The combination of the TBox and the ABox forms the knowledge base described through ontologies.

The main ontology elements are concepts (classes), properties, instances (individuals), and assertions. A *concept* represents a set of entities or things within a domain. *Properties* define either relations between an individual and a value, or between two individuals; called data type properties, and object properties, respectively.

The TBox module defines the concepts and properties in a domain in addition to specifying terminological axioms for every atomic concept. Axioms are used to constrain the range, and domain of the concepts, e.g. an airplane is an aerospace vehicle that has navigation capabilities. *Assertions* are statements about facts or beliefs. The ABox module contains a finite set of assertions for the classification of individuals, and their properties.

Inference over the ontology (TBox and ABox) is provided by a *reasoner*. The knowledge representation approach proposed in this paper is based on ontology and reasoner as described above. An ontological database captures information (data along with meaning) as to concepts, entities, and relations in order to build knowledge related to weather, flights, and airspace. The ontology enables artificial reasoning to make decisions based on the knowledge stored and the current situation estimates.

B. *Situation Awareness*

The decision-making process is based on the four-stage loop called Observe-Orient-Decision-Act (OODA) [14]. The OODA loop is essential for Situation Awareness (SAW) as well as Situation Assessment (SA) in information fusion [15]. Fig. 1 shows a SAW model.

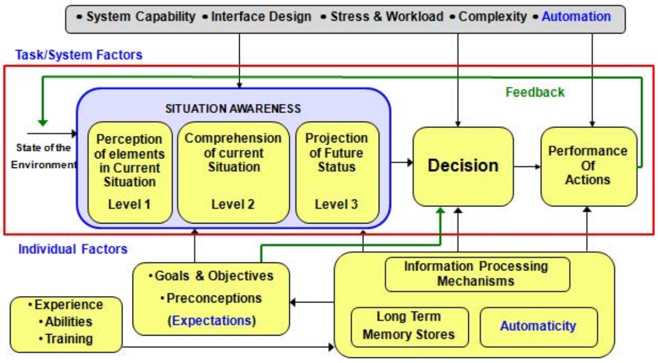


Fig. 1. Situation Awareness (SAW) Model

SAW allows systems to understand dynamic and complex environments, and operate with them. Cognitive SAW can be divided into three separate levels: perception of the elements in the environment, comprehension of the current situation, and projection of future status [16].

The concepts of the OODA loop enable a processing of information. The Observation stage is the SAW perception level. The Orientation stage takes into account the information acquired from the Observation stage and the knowledge represented by the ontology, to understand the situation (SAW comprehension level). The Decision stage is carried out at the SAW projection level. The Action stage closes the OODA loop by carrying out actions according to the adaption made in the previous stage.

SAW involves the events, states, condition, and activities of the environment dynamics as to time and space from which some situations arise (in particular those changes that occurred in the environment over some time interval). A *situation* is defined by a specific state after a sequence of events (with intermediate states, and activities with pre and post conditions). The situation is concerned with the comprehension of the environment features, and with the evolvement of these features over time.

SAW decision making mechanisms are critical for problem-solving processes that are preformed every time step for a situation from which data is collected at level 0 information fusion according to the Data Fusion Information Group Model [17, 18].

C. *Situation Assessment*

Situation assessment takes place at level 2 (SAW comprehension) in data fusion models. The Data Fusion Information Group Model levels include (Fig. 2):

Level 0 – Data Assessment
Level 1 – Object Assessment
Level 2 – Situation Assessment
Level 3 – Impact Assessment
Level 4 – Process Refinement
Level 5 – User Refinement
Level 6 – Mission Management

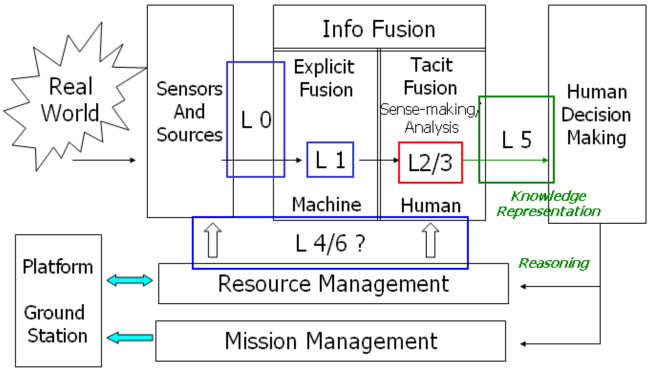


Fig. 2. Data Fusion Information Group (DFIG) model

In the DFIG model, the goal was to separate the information fusion (IF) (L0-L3) and resource management (RM) functions (L4-L6) [19, 20].

For UTM systems, there is both the resource management across sensors, users, and the mission (SUM) to coordinate with the objects, situations, and threats. The elements of the airspace need to be provided to air traffic controllers for enhanced SAW. Two integral concepts for Level 5 User Refinement information Fusion are displays to support usability [21] and information management systems that are trustworthy [22]. A binding element between the levels of fusion to reduce uncertainty is an ontology [23, 24].

IV. DATA FUSION IN AVIONICS ANALYTICS

This section is to discuss the ontological support as well as introduce the background for the case studies presented in section VI.

For air traffic management, System Wide Information Management (SWIM) including the ATM Information Reference Model (AIRM) [25], the Information Service Reference Model (ISRM), and the SWIM Technical Infrastructure (SWIM-TI) are being developed [26]. The concept of SWIM is an emerging concept to manage information for aviation systems for various ATM networks [27]. An AIRM example requiring ontologies is semantic filtering of notices to airmen [28].

A. *Information Acquisition*

Information fusion systems rely on the data that is acquired, processed, and utilized. Three steps are important in the analysis which includes data normalization, standardization, and templating for situation analysis.

1) *Data Normalization*

A fundamental knowledge of all fusion designs is that data is related to the collection as it is most likely processed as a probability (e.g., Bayes). To construct a data collection into a format for analysis is the process of normalization. For example, the absolute value of 10000 meters is relative to the environment. If a UAV was to be separated by the 10K limit of aircraft, it would be conservative for close-air operations. Hence the safe distance threshold should be normalized to the size of the aircraft.

2) *Standarized Data*

Data standardization includes the units, terminology, and definitions associated with the information. For the UAV airspace example, then the information should be standardized in time (zulu), distance (meters), and direction. An example for an ontology is Above Ground Level (AGL).

3) *Data Template*

To determine a situation, a third piece is useful (although there could be others), such that the template of knowledge that is available. A template could include the geographical terrain, cognitive processes, or action states. The template enables a rapid understanding of the situation from normal operations.

B. *The Role of the Ontology*

There is an emergence of interest of the use of ontologies for ATM and aerospace technologies [29, 30]. Examples include the NextGen and the SESAR systems. In order to frame the discussion. Fig. 3 highlights an example of how ontologies are included in an avionics system analysis. Using the incoming data from weather, flight profiles, and airports; that data needs to be accessed and normalized. Structuring the data is enabled with templates and ontologies. The structured ontology organizes the information (including syntactic and semantic metadata) for analytic tools. The resulting analytics supports visualization for aviators and Air Traffic Controllers (ATCs). Examples include mandates, current reports, and airspace information. Hence, ontologies afford a common method to organize, process, and share data.

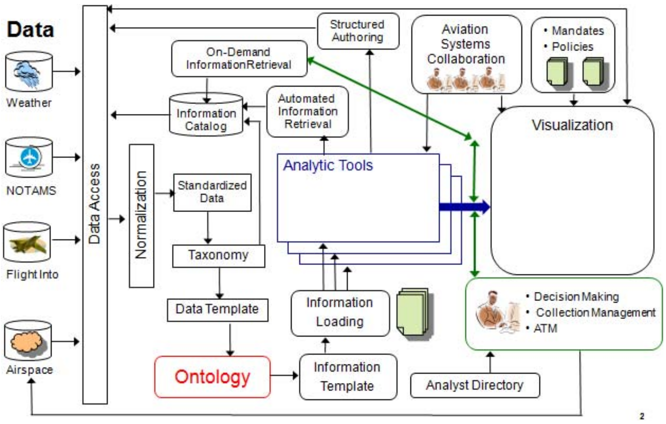


Fig. 3. Use of Ontologies for avionics analytics

V. ONTOLOGICAL KNOWLEDGE REPRESENTATION

This section describes the sematic definition for knowledge representation and knowledge-based reasoning queries.

A. *Ontology Semantics*

The ontology syntax (symbols and rules) is based on the Description Logic (DL) syntax structure. However, the implementation language for the ontology ultimately defines the syntax to semantically specify and describe ontology elements. The Ontology Web Language (OWL) and the Protégé tool [31] are selected to realize the ontology for the approach proposed.

The main OWL components to be created are the concepts (classes), properties for individuals, and instances of classes (individuals). These components are set for Avionics Analytics Ontology (AAO) as follows:

Classes (concepts); are conceptually defined as classes (special datatype) in object-oriented programming languages. Thus, they can be atomic classes (stand-alone ones) or associate classes (subclasses) along with “is-a” links. The AAO classes are: airspace, weather, vehicle (aircraft), person, location, and building. Fig. 4 shows the above is-a links between classes.

Properties (roles); are basically relationships between classes (or eventually individuals). The OWL allows for properties on objects (based on classes) or data (specific values). The first version of AAO only includes properties for objects as follows:

- hasAirspace
- hasLanding
- hasRoute
- hasStatus
- hasTakeoff
- hasWeather

Individuals; they are instances of classes (objects), e.g. a Boeing 747-800 is an individual (instance of the class “aircraft”).

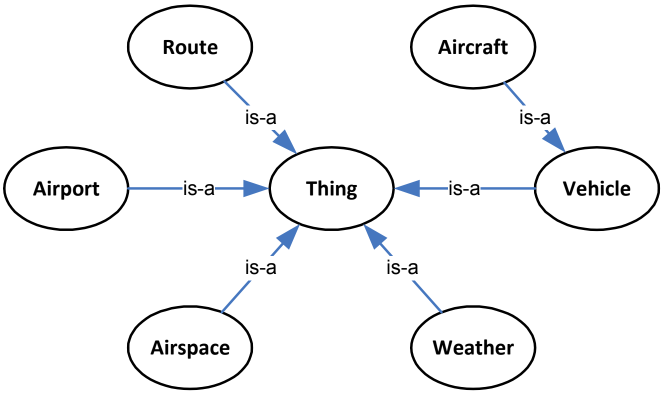
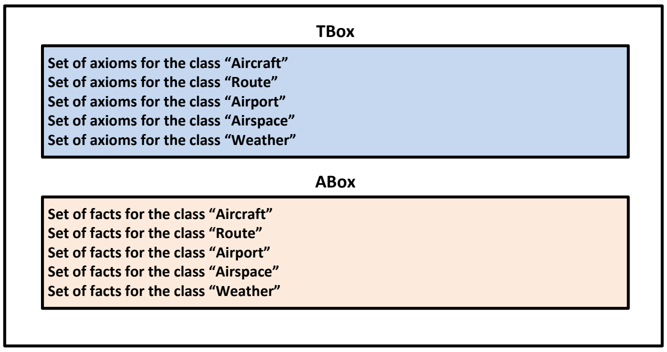


Fig. 4. Use of Ontologies for avionics analytics

Description Logic (DL) operators are considered as different types of property restrictions in ontologies: quantifier restrictions such as existential and universal restrictions, hasValue restrictions (counting operators such as *“less than or equal to”* and *“more than or equal to”*), as well as cardinality restrictions such minimum and maximum cardinality restrictions. Also, complex classes can be created by means of simpler classes described based on logical operators like *“or”* and *“and”*.

Property restrictions along with classes and individuals are the building block to define axioms. A terminological axioms (in particular, based on operators such as inclusion, equivalence, etc.) are in the TBox. A set of assertional axioms (facts or assertions) are in ABox. The TBox axioms, and the AAO ABox axioms are shown in Fig. 5. Both, the ABox and the TBox, form the AAO knowledge base. Details of the TBox and ABox are in the Appendix.



TBox

Set of axioms for the class “Aircraft”
Set of axioms for the class “Route”
Set of axioms for the class “Airport”
Set of axioms for the class “Airspace”
Set of axioms for the class “Weather”

ABox

Set of facts for the class “Aircraft”
Set of facts for the class “Route”
Set of facts for the class “Airport”
Set of facts for the class “Airspace”
Set of facts for the class “Weather”

Fig. 5. AAO knowledge base: TBox and Abox

B. *Ontonlogy Reasoning*

The Protégé tool allows for selecting a reasoner from a list of seven different reasoners (classifiers). Reasoners are the engine for the knowledge-based reasoning queries. They not only apply inference rules but also check semantic consistency on ontologies. These reasoning engines are able to deduce logical questions from axioms defined in ontologies.

Fig. 6 shows the asserted classes of the AAO. Aircraft have routes which in turn have a start point (departure or takeoff from an airport) and an end point (landing in an airport). Airports have their own airspace that is part of a larger airspace. Airspaces have weather conditions as well as air traffic.

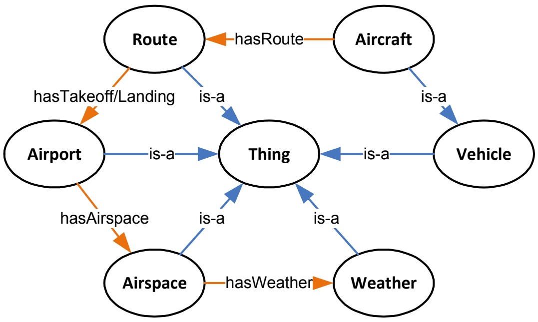
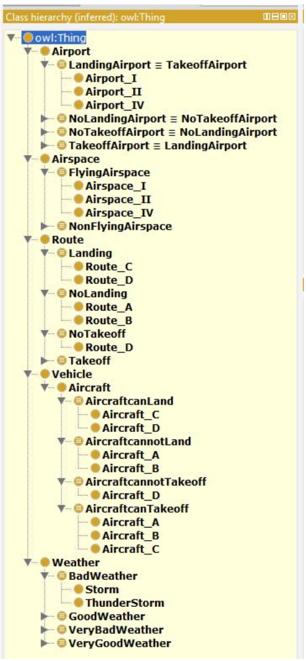


Fig. 6. Asserted AAO classes

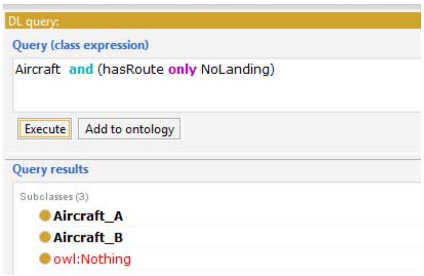
Fig. 7 shows the inferred classes of the AAO. This figure shows some example of AAO inferences as follows (from top to bottom). Airport I, II, and III are take-off and landing airports (aircraft can take off and land). Airspace I, II, and IV are flying airspace. Route C and D have landing. However, Route D has no take-off. Aircraft C and D can land in their corresponding airports. Bad weather includes storms and thunderstorms.



```
owl:Thing
  Airport
    LandingAirport ≡ TakeoffAirport
      Airport_I
      Airport_II
      Airport_IV
    NoLandingAirport ≡ NoTakeoffAirport
    NoTakeoffAirport ≡ NoLandingAirport
    TakeoffAirport ≡ LandingAirport
  Airspace
    FlyingAirspace
      Airspace_I
      Airspace_II
      Airspace_IV
    NonFlyingAirspace
  Route
    Landing
      Route_C
      Route_D
    NoLanding
      Route_A
      Route_B
    NoTakeoff
      Route_D
    Takeoff
  Vehicle
    Aircraft
      AircraftcanLand
        Aircraft_C
        Aircraft_D
      AircraftcannotLand
        Aircraft_A
        Aircraft_B
      AircraftcannotTakeoff
        Aircraft_D
      AircraftcanTakeoff
        Aircraft_A
        Aircraft_B
        Aircraft_C
  Weather
    BadWeather
      Storm
      ThunderStorm
    GoodWeather
    VeryBadWeather
    VeryGoodWeather
```

Fig. 7. Inferred AAO classes

The AAO inference allows reasoner to conclude that, for example, aircraft face severe weather conditions when landing in the destination airport. The reasoning query (DL query) to make such a question (what aircraft cannot land?) to the AAO and its answer are shown in Fig. 8.



```
Aircraft and (hasRoute only NoLanding)
```

```
Aircraft_A
Aircraft_B
owl:Nothing
```

Fig. 8. DL query on what aircrat cannot land

VI. APPLICATION EXAMPLES

This section presents application examples of the approach proposed in this paper. They are based on realistic scenarios.

A. *Case Study 1*

The first case study considers a scenario where three flights; Flight A, B, and C (Aircraft A, Aircraft B, and Aircraft C respectively), and four airports (Airport I, Airport II, Airport III, and Airport IV) are involved. Flight A takes off from Airport I and plans to land in Airport III. Flight B takes off from Airport II and plans to land in Airport III. Flight C takes off from Airport IV and plans to land in Airport I. Weather is very bad in the airspace of Airport III by the time Flight A and B have scheduled their landing. Fig. 9 shows the above scenario for case study 1.

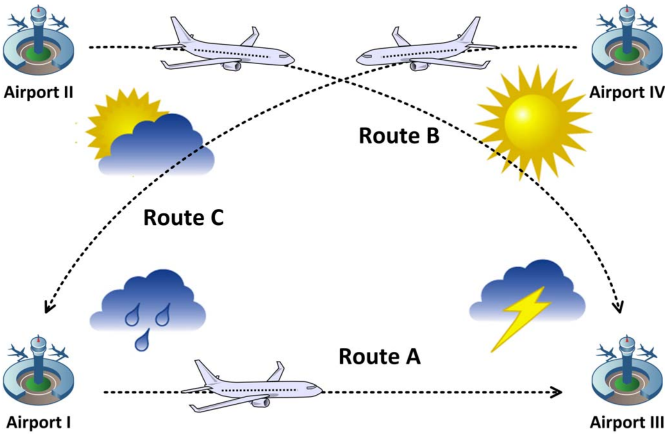
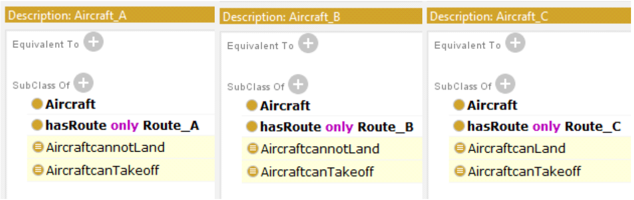


Fig. 9. Scenario for case study 1

The information provided by the AAO can be visualized by air traffic controllers to support their decisions on the above situation (also, aviators and pilots of remotely-piloted aircraft could make use of this information). They can run AAO queries as to the impact of the weather condition on the flight and suggestions about what to do or alternative routes. Fig. 10 shows a query for the above inquiry, and its response from the AAO.



Description: Aircraft_A
Equivalent To
SubClass Of
Aircraft
hasRoute only Route_A
AircraftcannotLand
AircraftcanTakeoff

Description: Aircraft_B
Equivalent To
SubClass Of
Aircraft
hasRoute only Route_B
AircraftcannotLand
AircraftcanTakeoff

Description: Aircraft_C
Equivalent To
SubClass Of
Aircraft
hasRoute only Route_C
AircraftcanLand
AircraftcanTakeoff

Fig. 10. Query inference results to assess situation from case study 1

The query inference results suggest that (from left to right): (1) Aircraft A and B (Flight A and B) can take off but they will not be able to land, and (2) Aircraft C (Flight C) can take off and it will be able to land.

B. Case Study 2

The second case study considers a scenario where four flights; Flight A, B, C, and D (Aircraft A, Aircraft C, Aircraft C, and Aircraft D respectively), and four airports (Airport I, Airport II, Airport III, and Airport IV) are involved. Flight A takes off from Airport I and plans to land in Airport III. Flight B takes off from Airport II and plans to land in Airport III. Flight C takes off from Airport IV and plans to land in Airport I. Flight D takes off from Airport III and plans to land in Airport IV. Weather conditions are very bad in the airspace en route to Airport I and Airport III (Aircraft B and C).

Airport I has four runways; Runway IA, IB, IC, and ID. All of them are not available. Airport II has two runways; Runway IIA, and IIB. Both runways are fully available (take-off and landing). Airport III has two runways; Runway IIIA, and IIIB. Both runways are fully available (take-off and landing). Airport IV only has one runway; Runway IVA which is only available for take-off (not for landing).

Fig. 11 shows the above scenario for case study 2.

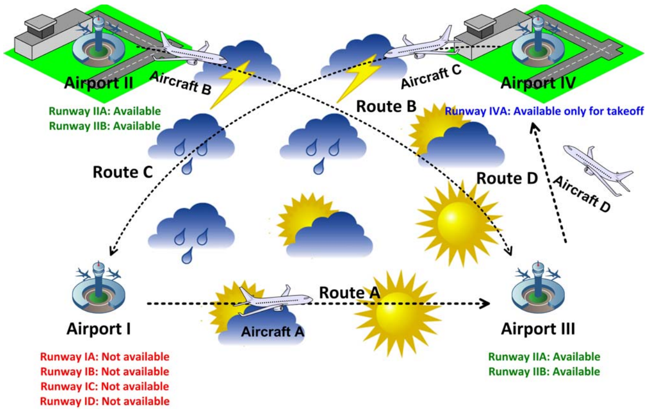
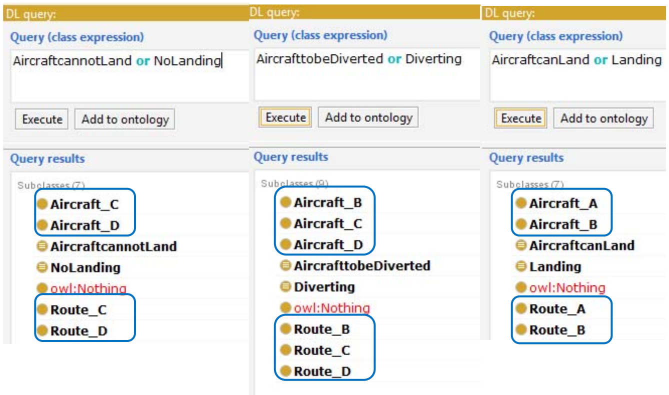


Fig. 11. Scenario for case study 2

As with case study I, information provided by the AAO can be visualized by air traffic controllers to support their decisions on the above situation (also, aviators and pilots of remotely-piloted aircraft could make use of this information). They can run AAO queries as to the impact of the weather condition on the flight and suggestions about what to do or best to do. Fig. 12 shows queries for the above inquiry, and its response from the AAO.



DL query:
Query (class expression)
AircraftcannotLand or NoLanding
Execute
Add to ontology
Query results
Subclasses (7)
Aircraft_C
Aircraft_D
AircraftcannotLand
NoLanding
owl:Nothing
Route_C
Route_D

DL query:
Query (class expression)
AircrafttobeDiverted or Diverting
Execute
Add to ontology
Query results
Subclasses (9)
Aircraft_B
Aircraft_C
Aircraft_D
AircrafttobeDiverted
Diverting
owl:Nothing
Route_B
Route_C
Route_D

DL query:
Query (class expression)
AircraftcanLand or Landing
Execute
Add to ontology
Query results
Subclasses (7)
Aircraft_A
Aircraft_B
AircraftcanLand
Landing
owl:Nothing
Route_A
Route_B

Fig. 12. Query results to assess situation from case study 2

The query results suggest that (from left to right): (1) Aircraft C and D (Flight C and D) will not be able to land as planned in route C and D, (2) Aircraft B, C, and D (Flight B, C, and D) should be advised to change routes as planned (Route B, C, and D), and (3) Aircraft A and B (Flight A and B) will be able to land as planned in route A and B.

C. Case Study 3

The purpose of the third case study is to show how the AAO can support decisions regarding aircraft proximity (based on the size of air vehicles and ATM/UTM). Thus, minimum distances between aircraft are normalized according to aircraft sizes (based on wingspans in this example).

Case study 3 considers a scenario for aircraft proximity. A flight (Aircraft A) is approaching airport I, and it finds itself in the proximity of another aircraft: a large airplane (e.g., Boeing 747), a small airplane (e.g., Cessna 400), and four UAVs (two remotely-piloted UAVs and two autonomous UAVs). Aircraft A plans to land at an airport where weather conditions are good. Surrounding aircraft are within the same controlled airspace class without any problem. However, they could fly in close proximity to Aircraft A when it is en-route to the airport. Fig. 13 shows the above scenario for case study 3.

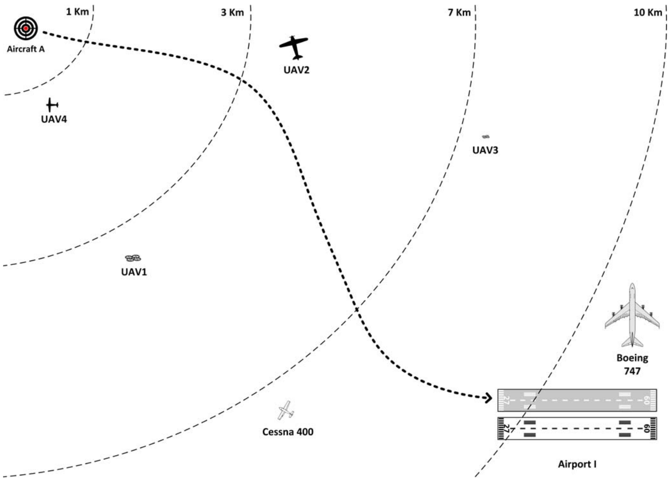
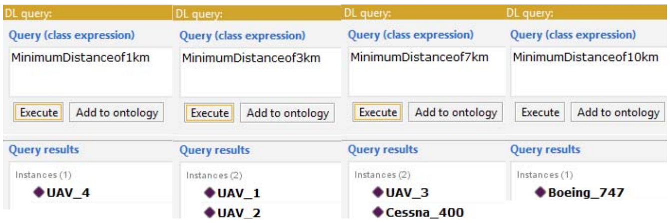


Fig. 13. Scenario for case study 3

The FAA defines airplane design groups according to aircraft wingspans. The Boeing 747 belongs to group V (52-65 m). The Cessna 400 and UAVs belong to group I (< 15 m). The suggested aircraft proximity in the AAO not only depends on the above wingspans but also on management of the aircraft based on whether the aircraft have a pilot or not (on-board, remote (contactable or non-contactable), and no pilot).

The information provided by the AAO suggests that all the aircraft in the scenario (Fig. 13) do not require to be separated to the same distance (as conventionally suggested; 10 km). This rather depends on the aircraft sizes. The Boeing 747 (due to its size and on-board pilots) requires 10 km. The UAV 1 and 2 can allow a distance of 3 km. The UAV 2 should keep a distance of 7 km (because its size) but it could be approached up to 3 km since it has a remote pilot who can be reached by ATM controllers. The Cessna 400 and UAV 3 require 7 km of minimum distance, even though the UAV 3 is small; it is autonomous (no pilot whatsoever). The UAV 4 is larger than the UAV 3 (no pilot) but it has a contactable remote pilot to deal with its waypoints. Query results are shown in Fig. 14.



MinimumDistanceof1km
Instances (1)
◆UAV_4

MinimumDistanceof3km
Instances (2)
◆UAV_1
◆UAV_2

MinimumDistanceof7km
Instances (2)
◆UAV_3
◆Cessna_400

MinimumDistanceof10km
Instances (1)
◆Boeing_747

Fig. 14. Query results to assess situation from case study 3

VII. Concluding Remarks

An implementation of Ontologies for NextGen Avionics Systems (ONAS) has been proposed. An operation framework and an ontology-based process to support decision making in advanced ATM/UTM systems have been presented along with examples of implementation. The AAO implementation is a simple but useful proof of concept for ONAS. The proposed ONAS approach includes a cognitive ATM/UTM architecture for avionics analytics and situation awareness (SAW) to maintain safe distances and alternative route planning for different weather conditions . The SAW approach proposed is intended to be used in civil aviation with potential use on board in autonomous UAVs in order to increase autonomy. It can also be taken into account in military operations. Results from three case studies along with application examples have been described. They are simple but also useful realistic scenarios for an ATM/UTM system which considers semantics from updates of weather maps, airport maps, and route maps. The above scenarios have discussed flight situations where the controllers' decisions can be made by means of the support of the ontological approach proposed.

Future research work will involve methods to improve the AAO and its implementation in order to include real data and equipment. In order to utilize collected data, there will be normalization and standardization of data processes as well as the integration of the other levels from the SAW model such as the threat analysis of a UAVs within the airspace that pose challenges to safe operations.

Appendix

The axioms of the AAO TBox are shown below.

Aircraft

Aircraft_A subclass of AircraftcannotLand and AircraftcanTakeoff
Aircraft_B subclass of AircraftcannotLand and AircraftcanTakeoff
Aircraft_C subclass of AircraftcanLand and AircraftcanTakeoff
Aircraft_D subclass of AircraftcannotLand and AircraftcannotTakeoff

Route

Route_A subclass of Landing and Takeoff
Route_B subclass of NoLanding and Takeoff
Route_C subclass of Landing and Takeoff
Route_D subclass of Landing and NoTakeoff

Airport

Airport_I subclass of LandingAirport and TakeoffAirport
Airport_II subclass of LandingAirport and TakeoffAirport
Airport_III subclass of NoLandingAirport and NoTakeoffAirport
Airport_IV subclass of LandingAirport and TakeoffAirport

Airspace

Airspace_I subclass of FlyingAirspace
Airspace_II subclass of FlyingAirspace
Airspace_III subclass of NoFlyingAirspace
Airspace_IV subclass of FlyingAirspace

Weather

ClearSky subclass of GoodWeather and VeryGoodWeather
CloudedSky subclass of VeryBadWeather
Hurricane subclass of VerygoodWeather
Rain subclass of GoodWeather
Storm subclass of BadWeather
Thunderstorm subclass of BadWeather
Tornado subclass of VerygoodWeather

The facts of the AAO ABox are shown below.

Aircraft

AircraftcanLand equivalent to Aircraft and (hasRoute only Landing)
AircraftcannotLand equivalent to Aircraft and (hasRoute only NoLanding)
AircraftcanTakeoff equivalent to Aircraft and (hasRoute only Takeoff)
AircraftcannotTakeoff equivalent to Aircraft and (hasRoute only NoTakeoff)

Route

Landing equivalent to Route and (hasLanding only LandingAirport)
NoLanding equivalent to Route and (hasLanding only NoLandingAirport)
Takeoff equivalent to Route and (hasTakeoff only TakeoffAirport)
NoTakeoff equivalent to Route and (hasTakeoff only NoTakeoffAirport)

Airport

LandingAirport equivalent to Airport and (has Airspace only FlyingAirspace)
NonLandingAirport equivalent to Airport and (has Airspace only NonFlyingAirspace)
TakingoffAirport equivalent to Airport and (has Airspace only FlyingAirspace)
NonTakingoffAirport equivalent to Airport and (has Airspace only NonFlyingAirspace)

Airspace

FlyingAirspace equivalent to Airspace and (not (NonFlyingAirspace))
NonFlyingAirspace equivalent to Weather and (hasWeather only VeryBadWeather)

Weather

VeryGoodWeather equivalent to Weather and (ClearSky or CloudedSky)
GoodWeather equivalent to Weather and (CloudedSky or Rain)
BadWeather equivalent to Weather and (Storm or ThuderStorm)
VeryBadWeather equivalent to Weather and (Hurrican or Tornado)

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